Fermilab Proton Projections for Long-Baseline Neutrino Beams

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Abstract

This note describes the rates of proton delivery that may be available in the future for long-baseline neutrino experiments. Several potential accelerator configurations are briefly described and analyzed in terms of their potential proton rates and schedules. Beam power is considered for variable primary proton energies between 30 and 120 GeV, delivered by the Main Injector.

1 Introduction

The Fermilab accelerators currently produce high-power proton beams to three users:

- Antiproton production for the collider program with 120 GeV protons, and an average beam power of 50 kW (peak power of 70 kW).
- Neutrino production for the NuMI beam with 120 GeV protons, and an average beam power of 170 kW (peak power of 270 kW).
- Neutrino production for the MiniBooNE beam with 8 GeV protons, and an average beam power of 10 kW (max power of 40 kW).

The above protons are produced using the 400 MeV Linac, 8 GeV Booster synchrotron, and 120 GeV Main Injector (MI) synchrotron. The Linac and Booster accelerate all of these protons, a portion of which are extracted to the MiniBooNE experiment, the rest going to the MI where they are further accelerated before being sent to either the NuMI beam or the antiproton source.

Increases in the proton power deliverable may come from three sources:

1. Improvements to the current accelerators to increase their capacity or efficiency.
2. Replacement of current accelerators with more capable ones.
3. Reuse of other Fermilab rings to streamline the proton accumulation and acceleration processes.

The possibilities discussed herein include combinations of the above techniques. The Main Injector is used in all plans as it is the only fast ramping accelerator at Fermilab that exceeds 8 GeV; for each scheme, however, the MI must be improved in some fashion. The Booster provides the dominant limitation on beam power; the schemes include its replacement, improvement, and methods to better use its beam. The potential schemes can be grouped into three broad programs:

The Proton Plan is a series of upgrades currently underway in the Linac, Booster and Main Injector. The plan is intended to improve reliability and increase beam power to the neutrino experiments. The Booster will be changed to allow a higher rate of operation at lower beam losses; the Main Injector will be changed to allow injection and slip-stacking of eleven Booster batches.

The upgrades are to be complete by 2008; realization of the improvements should occur over another year. During this period, a portion of the protons will still be used for antiproton production, a portion which can be redirected after the end of the collider. The tests that the Proton Plan puts upon the accelerators will be used to guide the details of further upgrade programs, particularly with regard to operation of the Booster..

Super NuMI (or SNuMI) consists of a series of upgrades to the Booster, Main Injector, and NuMI beamline, as well as the retasking of other Fermilab rings. SNuMI is intended solely to increase NuMI neutrino production after the conclusion of the collider run, primarily with the NOνA experiment in mind. SNuMI is in the planning stages, and has two possible phases: using the Recycler to slip-stack Booster beam while the MI is ramping; and using the Accumulator to momentum-stack Booster beam while storing beam in the Recycler and ramping the MI.

The Recycler would be used to load and slip-stack eleven batches of Booster beam. The combined beam would then be extracted to the Main Injector and accelerated to 120 GeV. Using the Recycler eliminates the time needed to load the Main Injector, increasing the beam power by 50%. Using the Recycler is only possible after the Tevatron is no longer used for high-luminosity collisions. It is anticipated that installation of the necessary components would occur in a five month shutdown at the end of the collider run, and that one to two years would be necessary to realize the intensity improvements; the cost of materials and services is preliminarily estimated to be around $10 M.

The Accumulator would be used to momentum-stack three batches of Booster beam. Six such combined batches would be stored in the Recycler, transferred to the Main injector, and accelerated to 120 GeV. A total of eighteen batches would be combined and accelerated in the time it took for eleven in the Recycler stage. Furthermore, momentum-stacking is expected to place looser tolerances on the Booster beam quality and to occur more efficiently than slip-stacking. Using the Accumulator would require disassembling Fermilab's antiproton storage capability. The civil construction and the majority of installation could occur in a one-year shutdown at the conclusion of the collider run. The Recycler stage could then be commissioned over a year, followed by a few-month shutdown, and further commissioning of the Accumulator stage over one or two years. A preliminary cost estimate for the Accumulator stage is $32 M in materials and services – in addition to the Recycler stage.

High Intensity Neutrino Source (or HINS – previously known as the Proton Driver) is an entire replacement of the Linac and Booster by an 8 GeV superconducting H^- Linac; it would also require substantial upgrades to the Main Injector and NuMI beamline.

The HINS program is currently in the R&D phase; as the bulk of the HINS is based on ILC technology, the R&D is focused on those devices that are not being developed as part of the ILC effort. The first 90 MeV of acceleration would be provided by very different devices than the ILC; most of the devices are also unique from other projects. Current planning has all of these devices being developed and integrated into a one-klystron linac. This device would be equivalent to the front-end for a HINS and is anticipated to be complete by 2010.

The results of the HINS R&D will be combined with ILC R&D to prepare new, more final, design and cost estimates. Previous estimates have put the project cost of a proton driver in excess of $300 M. Successful HINS and ILC R&D have the capacity to reduce the cost through better component performance, and to reduce contingency. A schedule for any HINS construction is likely to be funding limited, but take at least five years.

These upgrades have widely different time scales, costs, and impact upon the beam power. Furthermore, beam power scales differently with primary proton energy in the separate schemes. Some plans for new neutrino beams request a lower primary proton energy, so the next section will explore how the Main Injector cycle period is affected. The final section uses projected proton intensities and cycle periods to establish a rough schedule of proton power available over the next decade, and how that power changes with primary proton energy.

2 Main Injector Ramp

The Main Injector ramp period figures prominently in any determination of beam power as it comprises the denominator of all the calculations. A somewhat optimized ramp of the MI is shown in in Fig. 1, along with equivalent ramps to lower flattop energies for beams with lower primary proton energies. The ramp consists of several portions:

- An injection period (not shown in the figure) during which beam is injected from the previous accelerator. For current running and the Proton Plan this period is one fifteenth of second for each injection from the Booster, except the first. For all other scenarios the time is negligible.

- An upward parabola of momentum that is defined by the power supplies' abilities to ramp; it must also allow the RF bucket to deform adiabatically, avoiding emittance dilution. The duration of the parabola is nearly fixed.

- The linear ramp up is defined by the maximum rate beam can be accelerated by the RF, but still have adequate bucket area. Changing the slope requires extensive modifications to the RF system.

- The parabola just before the flattop is similarly fixed as the lower parabola.

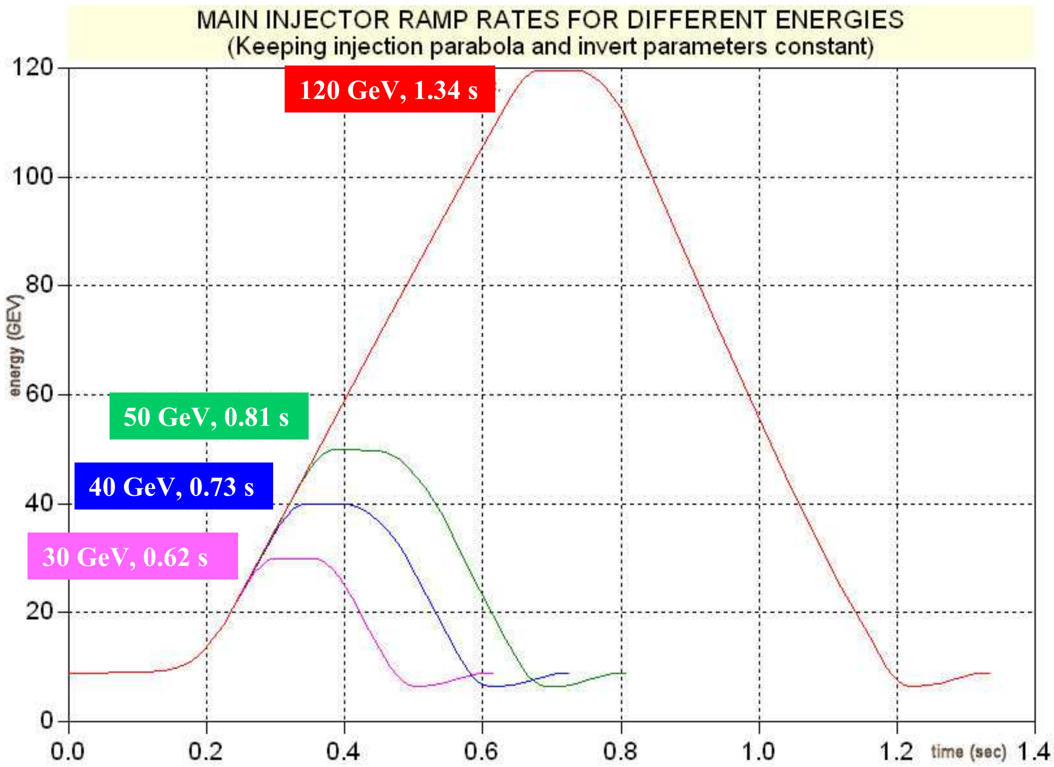

Figure 1: Example ramps of the Main Injector for an optimized cycle. The ramp periods are calculated for different flattop energies, while keeping other parameters the same: ramp rates, parabolas, hysteresis dip, and dwell times.

- The flattop extends for a period to allow the power supplies to regulate. Significant distortions persist for tens of milliseconds after the end of the parabola.
- The downward parabola and ramp are limited only by the power supplies, and are faster than the upward ramp.
- A hysteresis dip is necessary at the end of the down ramp to precisely reset the injection field. This dip may be modified, but only with extensive experimentation.
- An extended injection dwell time is necessary to reduce regulation oscillations, like at flattop.

With some optimizations, Fermilab engineers predict that the 1.33 s cycle shown in Fig. 1 is realizable. With further upgrades a cycle as short as 1.2 s may be possible, but would test the capabilities of the current RF system and require very quick regulation of the magnet currents at injection and extraction.

The 1.33 s cycle period consists of 0.44 s of fixed time, and 0.89 s of time proportional to the final energy of the beam. These numbers are used in the next section to perform scaling of the beam power with energy for the different upgrade scenarios.

3 Power Projections

The expected proton intensities and Main Injector cycle periods for the scenarios are presented in Table 1. The beam power presented is the peak average possible when the accelerators operate at their maximum intensity and repetition rate. The cycle period is longer for the current complex and proton plan because of the filling time from the Booster and that the MI ramp has not been optimized.

In practice, the long-term average beam power delivered to the target is always lower than the peak average beam power in Table 1. Such inefficiencies can be programmatic issues (e.g. beam sharing), accelerator downtimes, beamline downtimes, machine studies, and scheduled shutdowns. The accumulated effect of these inefficiencies has been studied for planning purposes, and is different in the different scenarios. The Proton Plan has developed detailed annual prjections of beam power for the near future. For simplicity in the later scenarios, we conglomerate all effects into an effective number of time per year at which the accelerators run at the peak power. Recent history has suggested this number is $\sim 1.7{\times}10^7$ seconds per year. The number is probably conservative for the HINS and later stages of running. The HINS is potentially simpler to operate than the Linac and Booster, and would at least be newer. Also, in general, experience gained through operations should allow more efficient operation of the complex.

The beam powers and effective uptime per year are combined with anticipated schedules to calculate the integrated protons that would be delivered in each year; these values are presented in Table 2. The Proton Plan, being underway, has concrete goals for its capabilities. The SNuMI stages are intended to be installed in 2010 and commissioned thereafter – as the Accumulator stage is a greater disruption to the complex it takes a longer time to reach its potential. The HINS prediction is an arbitrary start time, choosing a construction start in 2010 and lasting for 5 years, with a yearlong shutdown for integration in 2015 – no such schedule exists.

Scenario	**Proton Intensity** (10^{12} protons)	**Cycle Period** (s)	**Beam Power** (kW)
Current Complex	33	2	320
Proton Plan	49	2.2	430
SNuMI – Recycler	49	1.33	700
SNuMI – Accumulator	83	1.33	1200
HINS	150	1.33	2200

Table 1: Projected proton intensities and powers in the upgrade schemes, a portion of which can be used for neutrino production. The Main Injector cycle period is set by the ramp and filling time; a marginal improvement in the ramp period is expected in SNuMI or HINS, and the filling time is eliminated as well. The beam power is that calculated for 120 GeV protons, and would be the total available for all users (including antiprotons).

	Current Complex	Proton Plan	SNuMI – Accumulator	HINS
2006	2.3×10^{20}	2.3×10^{20}		
2007	2.3	2.8		
2008	2.3	3.1		
2009	2.3	3.4		
2010	3	4	0	
2011	3	4	5	
2012	3	4	7	
2013	3	4	10	
2014	3	4	10	
2015	3	4	10	0
2016	3	4	10	12
2017	3	4	10	20

Table 2: Expected annual numbers of protons deliverable for neutrinos in each of the possible scenarios. The later stages have numbers starting at the assumed time of installation, which temporarily reduces the running time; the HINS date is taken arbitrarily to be 2010 plus 5 years for construction. The first two columns increase in 2010 due to the conclusion of antiproton production.

Power Scaling

The scaling of the beam power with primary proton energy is shown for each of the scenarios in Fig. 2. The HINS performs best at lower energies as it does not depend on the Booster for producing protons. The SNuMI stages have kinks at 50 and 100 GeV, below which the deliverable beam power is limited by maximum Booster throughput, not the MI ramp.

This plot can be used to adjust the predicted rates presented in Tables 1 & 2. We note that deliverable proton power is always decreased by lowering the primary proton energy. Additionally, for all non-HINS scenarios the expectations of proton rate through the Booster increases for lower energies. The performance of the Booster at higher rates has not been established and will only come with accelerator improvements, hopefully realized through the Proton Plan.

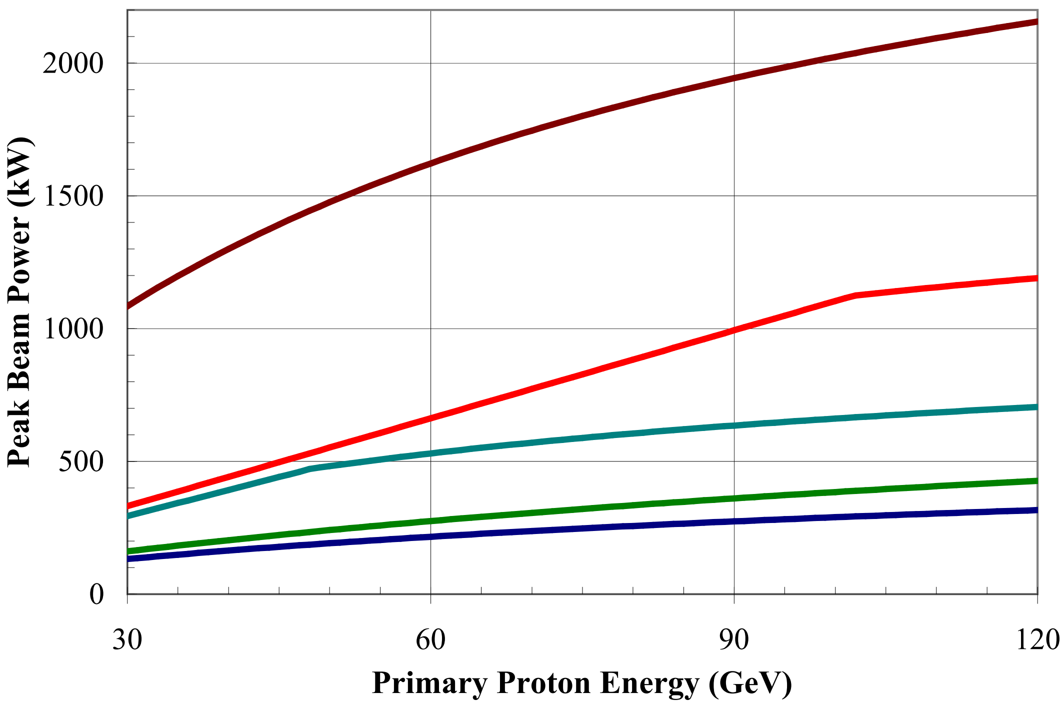

Figure 2: These curves express the effect of primary proton energy upon the projected proton beam power available in the several upgrade scenarios. From bottom-to-top, the lines correspond to the current complex (blue), Proton Plan upgrades (green), SNuMI Recycler stage (light blue), SNuMI Accumulator stage (red), and the HINS (brown).